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# COOLING OF PULSARS

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## ABSTRACT

Cooling rates are calculated for superfluid neutron stars of about 1 $M_{\odot}$ and 10 km radius, with magnetic fields from zero to about $10^{14}$ gauss, when possible internal friction effects are neglected. Our results show that most old pulsars are so cold that thermal ionization of surface atoms would be negligible. At an age of $10^6$ years and with canonical magnetic fields of $10^{12}$ gauss, the estimated stellar surface temperature is several thousand to a hundred thousand degrees. However, if we neglect magnetic fields and superfluid states of nucleons, the same surfaces would be about $10^6$ ° K.

## I. INTRODUCTION

The hypothesis that a pulsar is a rotating neutron star now seems quite well established. Almost all models which attempt to describe its observed slowing down or the mechanism which gives the observed radio pulses must ascribe to the neutron star a surface magnetic field of about $10^{12}$ gauss. Except near their upper mass limit, the interior has been predicted to be mostly neutron superfluid as soon as the internal temperature becomes small compared with 1 MeV (see, for instance, Ruderman 1968; Ginzburg 1969; Baym, Pethick, and Pines 1969). The effect of the magnetic field on the stellar surface region will be to reduce considerably the photon opacity. Superfluidity suppresses the normal heat capacity. Both effects, which have not been included in previous calculations of cooling rates (Tsuruta and Cameron 1966*a*), greatly accelerate the cooling rates. In this paper, emphasis is placed on consequences of these effects on the cooling of neutron stars during the stage when they can be observed as pulsars.

## II. FORMULATION AND RESULTS

For this purpose, we chose a neutron-star model with the following properties: stellar mass $M = 1.07\ M_{\odot}$, radius $R = 12.33$ km, and central energy density $\rho_c = 7.39 \times 10^{14}$ g cm$^{-3}$. (These are medium-mass models with the $V_{\gamma}$ type nuclear potential of Levinger and Simmons and the composite equations of state with equilibrium compositions which were constructed by Tsuruta and Cameron [1966*b*] and subsequently used by Hartle and Thorne [1968] and other authors.) Recently substantial improvements were made on neutron-star models, mainly by the use of nuclear potentials more realistic than those of Levinger and Simmons. In these improved models, a neutron star of the same mass has slightly smaller size and higher densities than in our models. (For instance, in the most recent models by Baym, Pethick, and Sutherland 1971, $R = 7.8$–$\sim$10 km and $\rho_c = (1$–$\sim$$2.6) \times 10^{15}$ g cm$^{-3}$ when $M = 1.07\ M_{\odot}$; see also Ikeuchi *et al.* 1971.)

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However, the effect of these small differences on the cooling was found to be negligible compared with the effects of the magnetic fields and superfluidity, and the general conclusions of this report will not be changed by the use of more realistic neutron-star models.

The cooling of a neutron star generally proceeds through neutrino-antineutrino emission from the interior and electromagnetic radiation from the surface. In the earlier stages of the cooling history when temperatures are high, neutrino emission dominates, while later at relatively lower temperatures photon emission is more significant. In our calculations we included neutrino emission from the plasmon process, the Urca process, the neutrino-bremsstrahlung process, the photoneutrino process, the pair-annihilation process, and the neutrino synchrotron process. We consider the history of a neutron star mainly after it has cooled down to several billion degrees, because profuse emission of neutrinos brings the star to that stage in a period much less than the age of the youngest pulsar. In the absence of magnetic fields and superfluidity, the Urca process is dominant (the plasmon process competes with it at higher temperatures and bremsstrahlung at lower temperatures [Tsuruta and Cameron 1966*a*]). Contributions by other mechanisms mentioned above turned out to be relatively minor. The major influence of the presence of magnetic fields in this regime is to reduce the Urca neutrino luminosity in a neutron star. Nucleon superfluidity also suppresses the Urca process significantly (Itoh and Tsuneto 1972). This is because the $\beta$-decay and electron capture of nucleons in the Urca process are hindered by the appearance of the superfluid energy gaps. (The other neutrino processes mentioned above are not affected by superfluidity, because only normal degenerate electrons, not superfluid nucleons, are involved.) Thus, for magnetic, superfluid neutron stars, the most dominant mechanism of neutrino cooling is estimated to be the plasmon process and the total neutrino luminosity is somewhat reduced.

Photon luminosity is described by the usual

$$L = 4\pi\sigma R^2 T_e^{\,4}\,, \tag{1}$$

where $\sigma$ is Stefan's constant and $T_e$ is the effective (surface) temperature of the star. Convection is very unlikely in neutron stars (Tsuruta and Cameron 1966*a*), so energy transfer will be governed by the opacity in the star. The total opacity $\kappa$ is generally expressed as

$$\frac{1}{\kappa} = \frac{1}{\kappa_r} + \frac{1}{\kappa_c}\,, \tag{2}$$

where $\kappa_r$ and $\kappa_c$ are the radiative and conductive opacity, respectively. Radiative opacity is due to various photoelectric processes (bound-free, free-free, and bound-bound transitions) and scattering by electrons (Compton scattering at $T > 5 \times 10^8\,{}^\circ$ K and Thomson scattering at lower temperatures). The relative importance of these processes depends in a complicated way on density and temperature. Generally in the atmosphere where densities are lower, electron scattering gives the greatest contribution to the opacity at higher temperatures but photoelectric processes become most important at lower temperatures; in the inner degenerate regions electron conduction is the major contributor to the inverse opacity.

In the presence of a superstrong magnetic field the opacity is greatly reduced (Canuto *et al.* 1972, hereafter referred to as Paper II). To a very rough approximation the radiative opacity is altered by modifying the corresponding photon cross-section according to:

$$\sigma_\omega(H) = \left(\frac{\omega}{\omega_H}\right)^2 \sigma_\omega(0) \qquad \text{for } \omega \ll \omega_H\,, \tag{3}$$

where $\omega$ is the radiation frequency, $\omega_H = eH/m_e c$ is the electron cyclotron frequency, and $\sigma_\omega(H)$ and $\sigma_\omega(0)$ are the photon cross-section with and without a magnetic field, respectively. This equation was derived in the case of Thomson scattering in earlier papers (Canuto 1970; Canuto, Lodenquai, and Ruderman 1971). It is also appropriate for free-free transitions, which are essentially classical, and a very crude approximation for bound-free transitions when the magnetic field strength is about $10^{12}$–$10^{13}$ gauss (see Paper II). Bound-bound transitions were found to be unimportant. We have applied the magnetic correction factor of equation (3) to the zero field opacities previously obtained by Tsuruta and Cameron (1966*a*). The Rosseland mean was used to take account of the frequency dependence. The radiative opacity thus obtained can be expressed as

$$\kappa_r(H) = a_r \kappa_r(0) ; \quad \text{with } a_r \propto (T/H)^2 . \tag{4}$$

The conductive opacity is similarly expressed as

$$\kappa_c(H) = a_c \kappa_c(0) . \tag{5}$$

The correction factor $a_c$ is generally a complicated function of a magnetic field, density, and temperature (for instance, see Canuto and Chiu 1969). However, for degenerate matter, the temperature dependence drops out and the factor $a_c$ decreases with increasing magnetic fields and decreasing densities. In the density regions where the conductive opacity plays a major role, the ratio $\kappa_c(H)/\kappa_c(0)$ decreases typically by a factor of from several to a few hundred for magnetic field strengths of the order of $10^{12}$–$10^{13}$ gauss (see Paper II for details).

The total thermal energy of a neutron star with "normal" matter is derived from the small thermal tail of the Fermi distribution function of degenerate fermions (neutrons, protons, electrons, muons, and hyperons if they are present) and the kinetic energy of nondegenerate heavy ions. The energy of heavy ions, however, will not be important, especially at temperatures significantly lower than the ion-lattice Debye temperature. For superfluid neutrons and protons, the specific heat is exponentially reduced:

$$C_s = C_n(T_c) 8.5 \exp(-1.44 T_c/T) , \qquad \text{for } T \ll T_c , \tag{6}$$

where $C_s$ and $C_n$ are the specific heat of the superfluid state and the normal state, respectively, and $T_c$ is the superfluid transition temperature. $T_c$ varies greatly for different assumptions of nuclear potential, effective mass, etc. According to Takatsuka and Tamagaki (1971) the (neutron) energy gap may be between a few tenths of an MeV and several MeV, so that the corresponding $T_c$ should lie between $10^9$ ° and nearly $10^{11}$ ° K. If $T_c$ is as high as the upper limit, nucleon specific heat will be insignificant compared with that of the electrons. On the other hand, if we take the lower limit for the value of $T_c$, the contribution of nucleons will not be negligible until the internal temperature becomes less than about $3 \times 10^8$ ° K. Both extremes are exhibited in our calculations to show the present measure of uncertainty in superfluid transition temperatures.

Results are summarized in the figures. Internal temperatures and surface temperatures are plotted as a function of time in figures 1 and 2, respectively, for varying strengths of magnetic fields. In the solid curves, neutron and proton thermal energies are neglected so that electrons are the major contributor to the total thermal energy. This corresponds to high-temperature superfluidity (with $T_c \sim 10^{11}$ ° K). In the dashed curves, superfluidity is neglected and the heat capacity comes mainly from the thermal tail of the degenerate neutrons. Hence for a given magnetic field strength, the corresponding solid curve and dashed curve approximate the upper and lower limits, respectively, for the heat-capacity effects of superfluidity. The crosses indicate the points where photon luminosity takes over from neutrino luminosity as the main cooling mechanism. (Magnetic fields are expressed by the ratio $\theta \equiv H/H_q$, where $H_q = m_e^2 c^3/\hbar e = 4.41 \times 10^{13}$ gauss.)

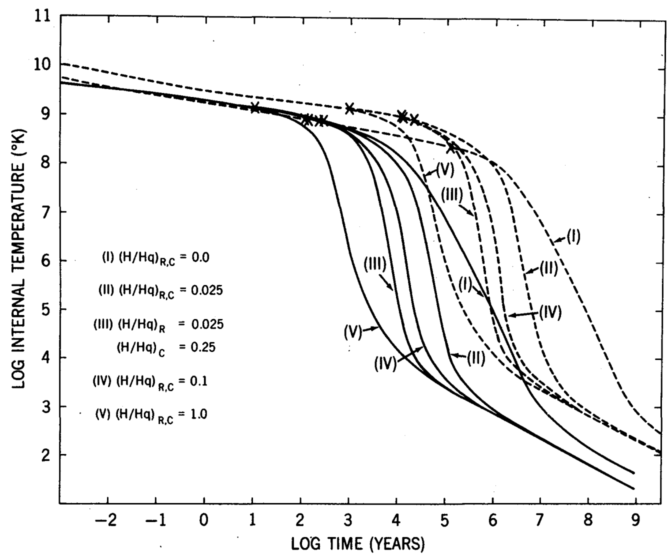


FIG. 1.—Internal temperature as a function of time, for varying strengths of magnetic fields. The models (I), (II), (IV), and (V) have the constant magnetic field of $\theta \equiv H/H_q = 0, 0.025, 0.1$, and 1, respectively. The models (III) are for $H/H_q = 0.025$ in the radiative opacity regions and $H/H_q = 0.25$ in the conductive opacity regions. The solid curves approximate the upper limit for the heat-capacity effects of superfluidity. In the dashed curves superfluidity is neglected.

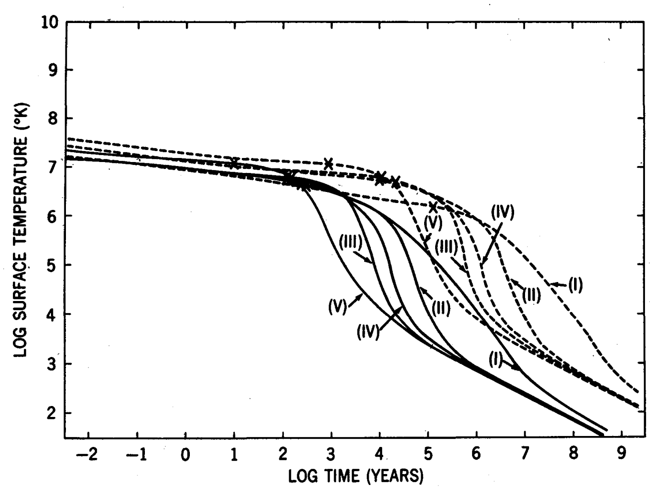


FIG. 2.—Surface temperature as a function of time, for varying strengths of magnetic fields. Notations are the same as in fig. 1.

In figure 1, the internal temperatures are lower for solid curves (high temperature superfluidity) than for dashed curves (no superfluidity) at a given magnetic field strength (with $H \neq 0$). This is because the total thermal energy is decreased for superfluid matter. From equation (4) we note that the ratio $\kappa_r(H)/\kappa_r(0)$ decreases as $(T/H)^2$ and for sufficiently cool neutron stars the atmosphere becomes transparent for photons with certain directions and polarizations. When this point is reached, the opacity is governed by electron conduction in the degenerate layers beneath the stellar surface. These layers also become increasingly transparent as the star becomes colder, because the degeneracy spreads to outer regions of lower densities with decreasing temperatures.

It appears that during the earlier periods while the star cools by neutrino emission, surface temperatures are somewhat higher at a given age in the presence of stronger magnetic fields. This is because the difference between the internal temperature and the surface temperature decreases due to the increased transparency of the strongly magnetized atmosphere, while the dominant neutrino luminosity is decreased. This effect becomes significant when the magnetic field strength becomes higher than about $10^{13}$ gauss (see fig. 2). In the presence of strong magnetic fields, the temperature drops fairly suddenly soon after electromagnetic radiation overtakes neutrino emission as the major cooling mechanism. This is because the atmosphere transparency increases at a growing rate as the temperature drops until the opacity almost vanishes. Exactly when this sudden cooling takes place depends critically on the field strength and the state of superfluidity.

It is quite possible that the interior magnetic field is stronger than the value at the surface. The models labeled (III) in the figures were constructed to see this effect. In these models the magnetic field at the surface is $H/H_q = 0.025$, the same as in models (II), but the magnetic field is increased by a factor of 10 (times the surface value) beneath the surface where the conduction dominates the inverse opacity. We see that the cooling rates are significantly increased for these models, more than the rates for the models (IV) with a constant magnetic field of $H/H_q = 0.1$.

An interesting result is that most pulsars may be very cold. Greenstein (1971) has pointed out that internal friction may generate enough heat to maintain the surface temperatures of certain pulsars somewhat above the values estimated here. (Such a possibility was first suggested by Cameron 1970.) The magnitude of these frictional effects, however, depends upon the strength of the coupling between the charged and the superfluid components of the star, and quantitative estimates for all the possible ways this may occur are not yet available. The average age and field strength of pulsars appear to be a few million years and about $10^{12}$ gauss, respectively (see, for instance, Gunn and Ostriker 1970). For this age and field strength, the stellar surface temperature is a little less than 1000° K for the solid curve (the exaggerated superfluidity) and about a factor of $10^3$ higher for the dashed curve (without superfluidity), for models (II) in figure 2. The actual value would be somewhere between these two extremes. However, pulsars are expected to have superfluid nucleons at internal temperatures much lower than the minimum calculated value of $T_c(\sim 10^9$ ° K). It is estimated that the actual surface temperature is about a few thousand to nearly a hundred thousand degrees (if frictional heating is negligible). In the absence of a magnetic field and superfluidity, the surface temperature of a neutron star of the same age is almost 1 million degrees.

For older pulsars, thermal ionization of atoms in the atmosphere may be negligible; an ionization energy of a few hundred eV is required at $H \sim 10^{12}$ gauss (Cohen, Lodenquai, and Ruderman 1970) while the atmospheric temperature may drop to less than $\sim 10^5$ ° K. (The heating effect of crust-core rotation slippage is the main uncertainty.) The surface of the neutron star is very likely iron, and this would make the ionization even more difficult. Therefore, if radio pulsars depend upon electrons streaming from the surface of a neutron star, decreasing surface temperatures below $\sim 10^5$ ° K may gradually turn off the pulsar (see Ruderman 1971).

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